Cicada's wings as determinant factor for the sound emission: The case of *Quesada gigas*.

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Cicadas (Homoptera:Cicadidae) are insects able to produce loudly songs and it is known that the mechanism to produce sound of tymballing cicadas works as a Helmholtz resonator. In this work we offer evidence on the participation of the wings in a high quality resonating process which defines the details of the acoustic properties of the calling song. The study is carry on *Quesada gigas* species and it is dividied in three stages: (i) the acoustical characterization of the abdominal cavity, (ii) the record and calculation of frequency spectrum of the calling song, and (iii) the measurement of the vibration modes of the wings. The comparison between all the results unequivocally show the dramatic influence of the wings in the moment in which the insect emits its calling song.

I. INTRODUCTION

Cicadas is the generic name of more than 1500 species of insects belonging to the Homoptera order, Cicadidae family[1]. Distinguishing them from other insects, cicadas are able to accomplish collective behaviors[2,3,4] and rich communicational codes[5,6]. In particular, males cicadas have modified organs to produce sounds in order to attract conspecific females and to prevent predators[7,8]. It is well-accepted that the sound-generator apparatus of typical cicadas works as a Helmholtz (bottle-shaped) resonator[9]. However, the calling song of cicadas is a species-specific sound that shows complex frequency spectra which evidence the participation of other mechanisms in the sound production. This is the case of *Proarna dactyliophora* Berg, *Proarna bufo* Distant, *Dorisiana drewseni* (Stål), *Dorisiana viridis* (Olivier) and *Quesada gigas* Olivier, species occurring in Santa Fe city (Argentina) and its outskirts ($31^o38'$ S latitude, $60^o42'$ W longitude)[10,11]. In this work we are going to focuss on the case of *Q. gigas*, the only species with a broad distribution covering North to South America[12]. They have a high size reaching a corporal length of (43 ± 4)mm (mean $\pm$ s.d.)[10] and its song is distinctive from other species since it sounds as a "whistle". Likewise that in the rest of typical or tymballing cicadas, its sound-generator apparatus is composed by a pair of stiffened membranes, the tymbals, placed dorsolaterally in the first abdominal segment. Two muscles are attached to the tymbals, the so-called tymbal and the tensor muscles. The tymbal muscle has great dimensions and due to strong contractions buckles the membrane inwards for then to recover the initial situation because of the elastic energy stored. The tensor muscle does not work in opposition to tymbal muscle but it changes the elastic properties of the tymbal membrane and can modify the amplitude, the time interval or frequency of the acoustic signal[13]. The generated pulse is amplified by the almost hollow abdominal cavity, and radiated by the tympana[9]. Understood in this way, the sound-producing apparatus of tymballing cicadas is a pulsed Helmholtz resonator in which the abdominal sac is the resonant cavity, the tympanal opening is the neck and two cuticular flaps, the opercula, regulate the neck area[14,15]. The predominant frequency of a Helmholtz resonator is given by the geometry of the system[16] or as in this case, by the morphometric features of each species. Thus, it is possible to find a scaling law correlating the frequency of the song and some typical length[17]. However, the scaling law fails in some species as is the case of *Q. gigas* where the predicted calling frequency is roughly 4 kHz while the actual predominant frequency is the order of 1 kHz[10].

In this paper we will show how the wings of *Q. gigas* species dramatically participate in a high-quality resonant process defining its calling song being this, up to our knowledge, the first evidence about cicada's wings as determinant factor in sound production.

II. METHODS

In order to reach the objectives of this work, we proceed in three stages: (i) Firstly we characterized the response in frequencies of the abdominal cavity, then (ii) we recorded the calling song of *Q. gigas* and we calculated its frequency spectra, (iii) we measured the normal vibration modes of the wings and finally, we compared all the results to arrive to the final conclusion.

The physical characterization of the abdominal cavity as acoustical resonator should be done extracting the response in frequency after exciting it with a brief pulse. Experimentally we are able to obtain this response taking advantage of the information given by the distress or protest call. In our case, this song was recorded holding the animal with the hand and moving the wings towards a side.

The calling songs were recorded in the natural habitat of this species at different light hours, temperatures

greater than 30 C and covering urbanized and non-urbanized areas of Santa Fe city, Argentina.

Both, distress and calling song were recorded with SONY TM-343 and Panasonic RQ-L309 magnetic tape recorders, provide with electret condenser microphones which guarantee a planar response in the frequency range of interest. Then, the records were digitalized with a rate of 22050 data per second.

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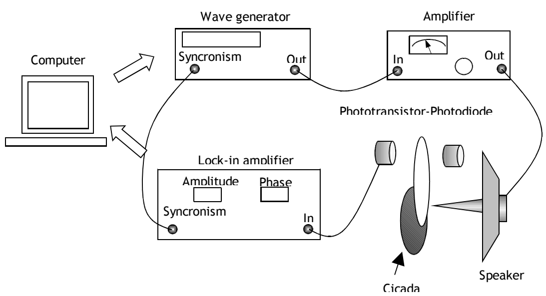

FIG. 1: **Experimental setup to measure the vibrational normal modes of *Q. gigas* wings**. The light cone attached to the speaker stimulate by outside the wings with a controlled frequency just in the region where the tymbal membrane is placed. The wing's movement produces a shadow pattern over the light detector and the Lock-in amplifier guarantees the measurement of the amplitude of oscillation for the same frequency of the signal generator.

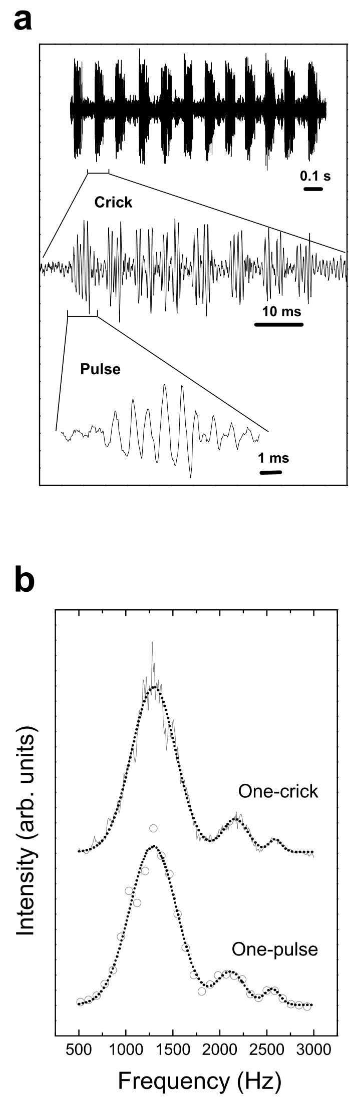

FIG. 2: **Physical characterization of the abdominal cavity of *Q. gigas***. (a) Oscillogram of distress call and details of crick and pulse. Records were digitalized with a rate of 22050 data per second. (b) Response function of the abdominal cavity resonator. The results correspond to an average on Fourier spectra ($n = 50$) of cricks and first pulses of the distress call.

III. RESULTS AND DISCUSSION

The adopted procedure to record the distress song assure us that the emitted sound is an unique feature of the pulsated of the muscle and tymbal membrane over the abdominal cavity. An example of this record is shown in Fig. 2a. The upper oscillogram show a series of brief emissions that we will name by the onomatopoeic word "crick". Each crick in turn, is composed by a train of 6-10 pulses. We ascribe each pulse to a consecutive contraction of the muscles buckling the tymbal membrane and its ribs so that this system works as a sort of Zeeman machine[18] in virtue of which it is possible to excite frequencies of the order of the kHz. Therefore, by performing the Fourier Analysis of the first pulse of each crick we can obtain the acoustical response function of the abdominal cavity. Figure 2b shows the frequency spectrum characterizing the cavity after having averaged 50 Fourier spectra corresponding to different cricks emitted by the same individual. Pulse and crick spectra are quite similar and a three-gaussian fit yields a main peak at (1290 ± 10) Hz with a half-height width of (500 ± 30) Hz for the pulse and (1296 ± 3) Hz and (478 ± 6) Hz for

the crick respectively.

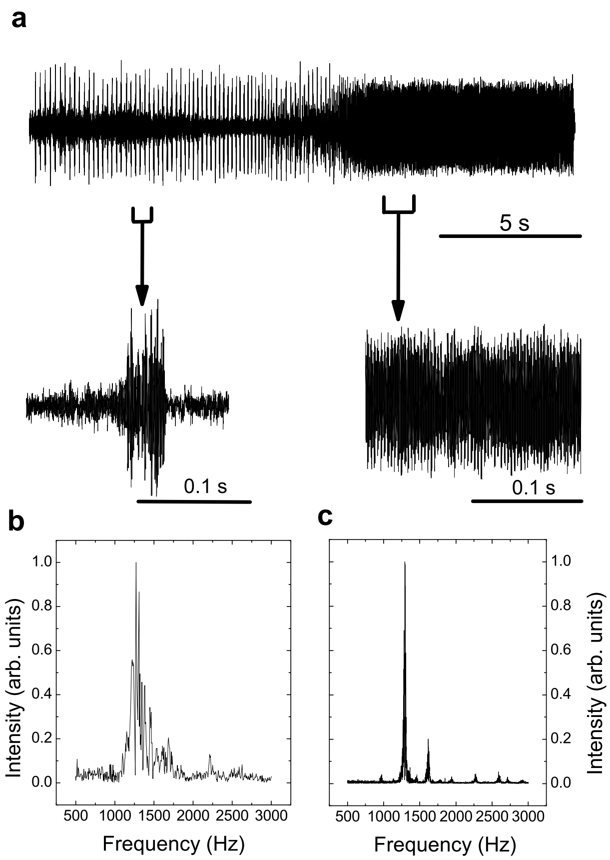

FIG. 3: **Calling song of *Q. gigas***. (a) Oscillogram of the complete song and details of a crick previous to the "whistle" sound, and of the sustained phase of the song. (b) and (c) Fourier spectrum of the crick and sustained sound respectively.

On the other hand, the response in time of each pulse lasts (6.5 ± 0.3) ms ($n = 442$), which allows us to infer that if the calling song of cicadas was a continuous sequence of pulses resonating into the abdominal cavity, the corresponding Fourier spectrum should be simply a set of peaks separated by (154 ± 7) Hz approximately and modulated by the one-pulse envelope function given by Fig. 2b. Nevertheless, the sustained phase of the calling song of *Q. gigas* does not agree with this conclusion as it can be observed in Fig. 3. The complete calling song lasts around 15-20 s and it is composed by three phases. Firstly, the animal emits a sequence of cricks, then occurs a short and unstable phase which precedes the sustained song. Figure 3a is the complete oscillogram with details of the first and third phases and Figs. 3b and 3c are their corresponding Fourier spectra. The sustained part of the song involves a very well defined spectrum with a main peak around (1294 ± 1) Hz, which is in good agreement with the main peak of the abdominal cavity. However, the width of this very thin peak is more than ten times lower than the corresponding to the Helmholtz-like resonator [(29 ± 1) Hz in this particular record] (Fig. 3c). Besides, there are noticeable differences in lineshape between cricks corresponding to the calling song (Fig. 3b) and protest song (Fig. 2b). Therefore, an evident conclusion arising from the comparison among Figs. 2b, 3b and 3c is that, with the purpose to produce the sustained song, *Q. gigas* adds a new mechanism in its sound-generator apparatus.

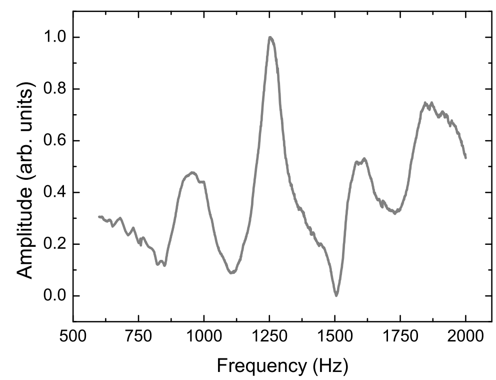

FIG. 4: **Measured amplitude spectrum for the wing movement** using the experimental setup of Fig. 1. The main peak is located at 1257 Hz nearly coincident with the main peak of distress and calling song.

Inspecting the morphology of tymballing cicadas, one may verify that the tymbal membrane is located dorsolaterally but clearly exposed to the outside and covered and in contact with the wings. This biological design notice us about the unavoidable interaction between the buckling membrane and the wings when the calling song is emitted. In order to quantify the relevance of this interaction we measured the normal modes of vibration of *Q. gigas* wings and we compared these results with the corresponding recorded songs. The amplitude spectrum is drawn in Fig. 4. In the region of frequencies of interest (600-2000 Hz) four peaks are discernible. The central peak is located at 1257 Hz, nearly coincident with the maximum of calling and distress song, and the lateral peaks are placed at 959 Hz, 1601 Hz, and 1878 Hz respectively.

In Fig. 5 we summarize a comparison among spectra corresponding to the pulse of distress call, the calling song and the square of the amplitude spectra of the wing's vibration modes since it is the quantity proportional to the acoustical power signal indeed. It had been mentioned that if the calling song was only the consequence of a regular pulsed over the abdomen, its Fourier spectrum should be represented by equidistant peaks modulated by the one-pulse envelope curve. By contrast, if we assume an interaction between wings, tym-

bal and abdomen, we can infer that deeps at 1110 Hz and 1508 Hz in the wing spectrum depress the corresponding peaks that should appear due to the beating. Moreover, the slight asymmetry of the main peak in the intensity wing spectrum allows the occurring of a small peak at 1440 Hz in the calling song. In this way, the interplay among tymbal, abdomen and wings produces an energy optimization over the main peak defining the sustained part of the calling song of *Q. gigas*.

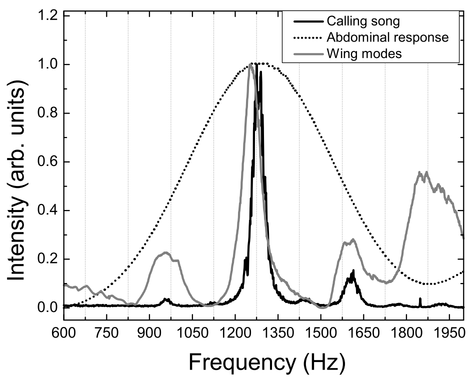

FIG. 5: **Overall comparison** between calling song (black line), acoustical response of abdominal cavity (dotted curve) and experimental normal modes (intensity spectrum) of the wings of *Q. gigas* (grey line). All the spectra are normalized by fixing their maximum value equal to one.

Fig. 6 includes additional analysis enforcing the comprehension of the wing-abdomen-tymbal coupled resonator forming the sound-producing system. Fig. 6c is the product between the frequency response of the pulse (Fig. 6a) and an analytical function simulating an assumed regular pulsed of the tymbal (Fig. 6b). Now, by multiplying this curve by the intensity spectrum of the wing's vibrational modes (Fig. 6d) it is obtained the curve shown in Fig. 6e, which is very much similar to the calling song spectrum (Fig. 6f). In conclusion, the abdomen morphometry (represented by Fig. 6a), the tymbal beating (simulated by the function in Fig. 6b) and the geometry and stiffness of the wings (signed by the Fig. 6d) strongly interact in order to define the acoustic feature of the calling song of species *Q. gigas*.

IV. CONCLUSIONS

The Fourier spectra of the sound emitted by cicadas can be used as taxonomic tool due to the clear differences between species. In the species *P. dactyliophora*, *P. bufo*, *D. drewseni*, *D. viridis* and *Q. gigas*, occurring in Santa Fe, Argentina, we had previously verified that the overall explanation of their frequency spectra can not be performed only with the identification of the insect as a Helmholtz-like acoustic machine. In this work we have

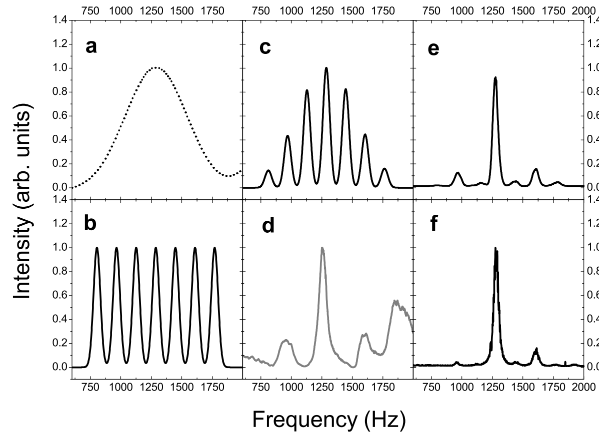

FIG. 6: **Reconstruction of the calling song spectrum of *Q. gigas***. (a) Abdominal acoustic response. (b) Simulation of the tymbal beating using gaussian functions with a half-width of 40 Hz and regularly separated by 160.9 Hz. (c) modulated beating arising from the product of (a) and (b) curves. (d) Intensity spectrum of the wing normal modes. (e) Simulated calling song frequency spectrum reached by multiplying (c) and (d) curves. (f) Real calling song spectrum.

found novel mechanisms in the sound production in cicadas. While not strictly a Helmholtz resonator, the abdominal cavity is actually the resonator which defines the value of the predominant frequency of the calling song. The quality of the sound, however is a consequence of a very fine interaction between the beating tymbal membrane and the wings, involving a selection of frequencies which allows to the species *Q. gigas* to produce an almost musical sound in its calling song.

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